Purpose: To provide a comprehensive and flexible method for handling time dependent quantities including interplay effects in proton beam scanning.

Methods:The time feature was devised to handle time-dependent quantities in the Monte Carlo simulation. Each time-dependent quantity corresponds to one time feature. A time feature can be expressed as a simple mathematical function or composed of more complex, pre-defined functions. The functions may be combined concurrently and/or consecutively so that users can customize complex time features. During simulation, time is set in one of two manners: 1. Randomly chosen time, suitable for handling continuous behaviors, or 2. sequentially-generated time, where time interval is equally divided. This time feature has been incorporated in TOPAS, a tool for particle simulation with Geant4, under development to make Monte Carlo simulation more accessible to both clinical and research physicists.

Results:The time feature has been deployed to simulate various proton beam scanning patterns in clinical proton beam nozzle. The patterns include parallel, raster, circular, saw-tooth, and Lissajous figure scans. Through the parameter management in TOPAS, time features for those scanning patterns were easily implemented. Dynamics of the beam including pulse shape, spot size, and movement were concurrently simulated. Randomly set time gave more accurate results when fewer histories were simulated, resulting in under-sampling when time was set sequentially, while the simulation time with the 2 methods was similar for the same number of histories.

Conclusions:Methodology has been developed to comprehensively describe time dependent behaviors in the Monte Carlo simulation and was assessed by applying to clinical proton beam scanning. A novel aspect of the method of separation of the time generators and time receivers has made it straightforward to handle multi time- dependent quantities and is therefore relevant to fully simulate interplay effects.

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